DESIGN CONSIDERATIONS FOR THREE-PHASE GRID CONNECTED PHOTOVOLTAIC INVERTERS

Raymond M. Hudson[1], Michael R. Behnke[1], Rick West[2], Sigifredo Gonzalez[3] and Jerry Ginn[3]

1) Xantrex Technology Inc. 161-G South Vasco Road, Livermore, CA 94550 USA
2) Xantrex Technology Inc. 3547-C South Higuera St, San Luis Obispo, CA 93401, USA
3) Sandia National Laboratories, Bldg 833, 1515 Eubank Blvd, Albuquerque, NM 87123 USA

ABSTRACT

This paper will discuss the design considerations for three-phase inverters for grid connected photovoltaic systems. Specific performance considerations are addressed including topology trade-offs, efficiency trade-offs, and maximum power point tracking. Additionally, utility interconnect issues will be examined including power quality and anti-islanding. Testing results will be provided for the Xantrex PV series of inverter products. These systems operate with a variety of PV panels and are designed to meet the UL-1741 utility interconnection standard. Power levels are from 5kW to 300kW, and the output is a nominal 208Vac. Experimental results showing successful operation are given for the 10kW system. Testing was performed at the Sandia National Laboratories Photovoltaic Systems Evaluation Lab in Albuquerque, NM.

INTRODUCTION

There are many design considerations in the development of three-phase inverters for grid connected photovoltaic systems. The design trade-off decisions are key to implementing a successful system as well as achieving customer satisfaction. Larger photovoltaic systems in the 5kW to 1MW range are becoming more common, increasing the importance of three-phase grid connected inverters to the photovoltaic industry. The key design considerations examined in this paper include the following areas: circuit topology, conversion efficiency, maximum power point tracking, power quality, anti-islanding and cost.

It is critical in the development of these inverter systems to obtain accurate test data to validate performance. Sandia National Laboratories has a unique facility in the Distributed Energy Technologies Lab (DETL). It is supported by the PV Program of the Department of Energy to evaluate power-conditioning equipment for manufacturers, utilities and end users. DETL has been used to measure the performance of distributed energy resources ranging in size from 70 watts to hundreds of kW. DETL test equipment includes photovoltaic arrays, battery banks, electrical loads (resistive, reactive, nonlinear, and motor), and ac sources (grid feeds, engine-generators, and solid-state arbitrary waveform generators).

In testing PV inverters, voltage and current measurements are acquired on both ac and dc sides of the equipment and are analyzed to evaluate key parameters including efficiency, distortion, output regulation, and load compatibility. Specialized tests are also performed including high-voltage surges, conducted and radiated radio-frequency emissions, and audible noise. Standardized test protocols have been developed for stand-alone and utility-interactive tests. In testing utility-interactive inverters such as the Xantrex PV series, abnormal utility conditions are simulated. These include transient voltage and frequency deviations and loss of utility.

Data is presented for the Xantrex PV series of inverters that was taken at the Sandia DETL facility. This data indicates both the type of data used to validate design considerations as well as the successful operation of these systems.

TOPOLOGY

The first significant decision that an inverter designer must make is the choice of an overall circuit topology. The PV array voltage and utility grid interconnect voltage drive the topology selection. There can be wide DC input voltage variations resulting from various combinations of array power, temperature and module configurations. The primary topology consideration is whether or not to use a DC to DC converter stage between the PV array and the DC to AC inverter block to pre-regulate the DC “bus” voltage. Block diagrams illustrating these options are shown in Figure 1. The inverter with a DC to DC converter stage will operate over a wider DC input range but with a cost premium and lower conversion efficiencies at most operating points. The topology that provides the best energy yield under a given set of operating conditions will be determined by the remaining system components.

Xantrex has reviewed these trade-offs and has selected the topology shown in Figure 2. This is a three-phase bridge where the DC bus is connected in parallel with and directly across the PV source. The PV units operate with a PV voltage window of 330 to 600 Vdc and the output voltage is 208Vac.

Systems using the PV Series inverters are configured with a 60Hz isolation/distribution transformer to step up the final utility line-tie voltage for more efficient power transmission. The single conversion provides high-efficiency power conversion and the isolation/distribution transformer provides flexibility of utility grid-tie voltage options. The transformer does, however, reduce the overall system efficiency.

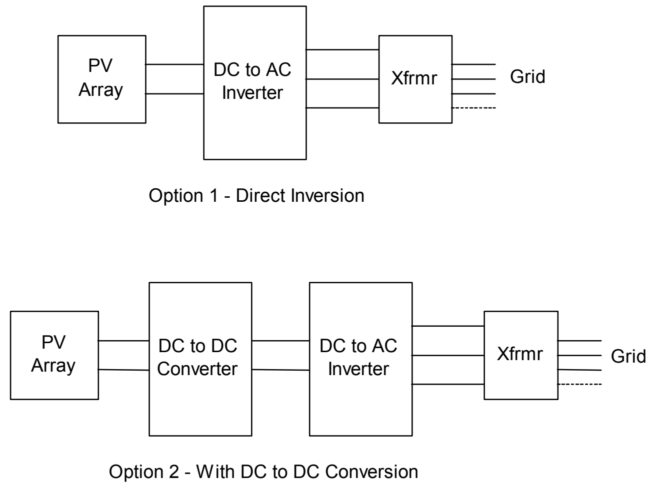

Figure 1. Topology Block Diagrams

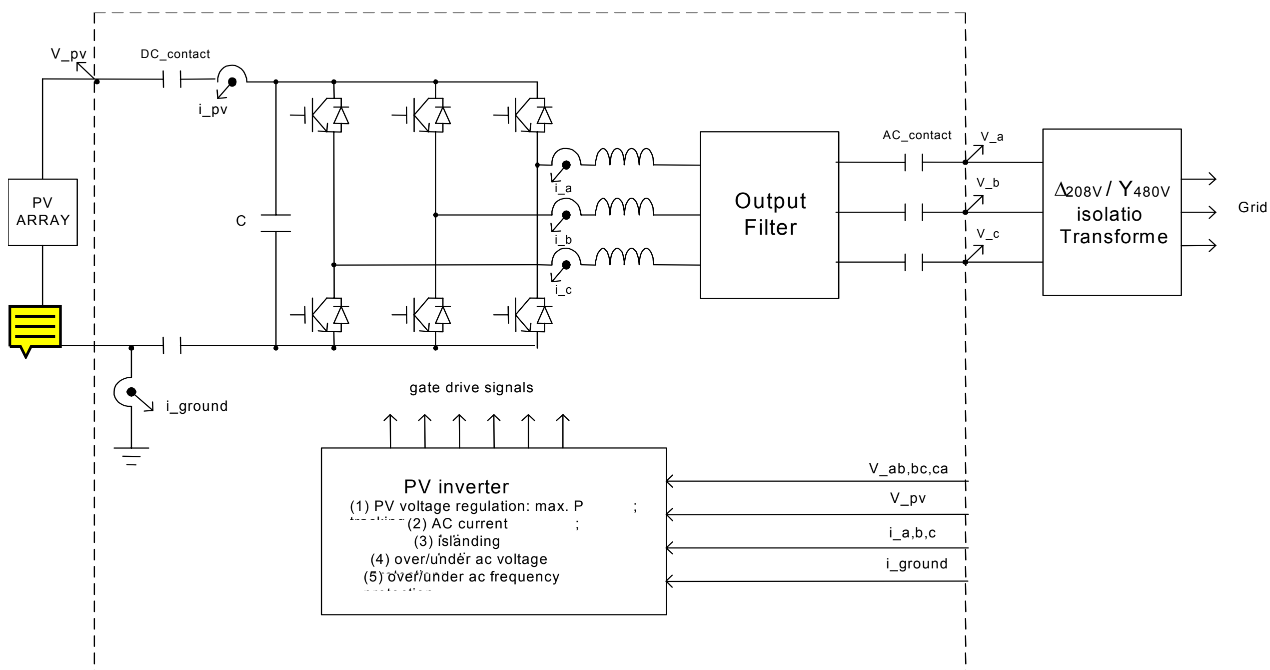

Figure 2. Xantrex PV Series Topology

EFFICIENCY

High efficiency is desirable for all inverters utilized in photovoltaic systems. Every watt that is lost in the inverter is power that is not delivered to the utility grid. For a given system AC power output, the cost of additional PV modules must be added in to compensate for inverter power conversion losses. The primary method of increasing efficiency is through the selection of inverter components with a focus on this factor. Key components for efficiency optimization include: transistor devices, magnetics, and parasitic loads. For the voltages and current levels in larger three phase systems, the preferred device at this time is the Insulated Gate Bipolar Transistor (IGBT). These devices are both robust and have relatively low losses. The device manufacturers continue to optimize the devices for lower conduction and switching losses. The selection of switching frequency is based on trade-offs between losses, magnetic component costs, power quality, cooling system requirements, audible noise, and equipment size and weight. Careful selection of components that present parasitic loads, such as fans, contactors and power supplies can significantly increase efficiency. Table 1 shows a qualitative view of these efficiency tradeoffs.

Table 1. High Efficiency Design Tradeoffs

Higher conversion efficiency via	Semiconductor costs	Magnetics costs	Heat removal costs	RFI generation	Size and weight	Overall circuit complexity
Lower switching frequency		increase	decrease	decrease	increase	
Lower semiconductor conduction losses	increase		decrease			
Natural convection cooling vs. forced convection			increase		increase	decrease
Switching auxiliary power supply vs. linear	increase	decrease		increase	decrease	increase
Lower dissipation snubbers				increase		increase

The Xantrex Technologies PV 10208 system was tested to determine its DC to AC conversion efficiency at Sandia National Laboratories. This data is shown in figure 2. Note that this efficiency includes the losses of the 60Hz transformer at the utility grid interface.

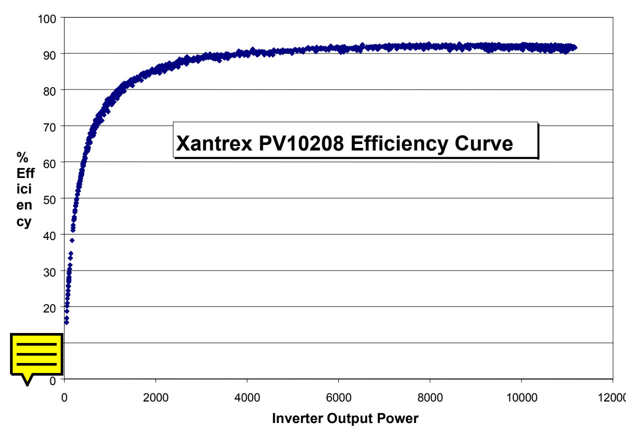

Figure 3. Xantrex PV Series Conversion Efficiency

Accurate inverter efficiency measurements are difficult to make. A power meter with 0.5% voltage and current measurement accuracy employing 0.5% current shunts will yield efficiency numbers for a 95% efficient inverter anywhere between 92% and 98%. Some manufacturers only specify a "peak efficiency" which is of little use to system designers or in making inverter value comparisons. Ideally, efficiency vs. power level curves should be given at different DC voltages throughout the maximum power tracking window. Conversion efficiency is very much a function of the DC operating point in any inverter. Comparative evaluation of inverter efficiency based on manufacturer's data is further complicated by the lack of a generally accepted inverter efficiency test standard. This type of standard method would be beneficial to the industry and end users.

MAXIMUM POWER POINT TRACKING

A key function that is integrated into the inverter system for photovoltaic applications is maximum power point tracking (MPPT). This algorithm operates to keep the system on the peak power point of the voltage versus current relationship of the connected PV array based on the array characteristics, available irradiance and module temperature (refer to Figure 5). Various algorithms for achieving this have been proposed or implemented including those in references [1] and [2].

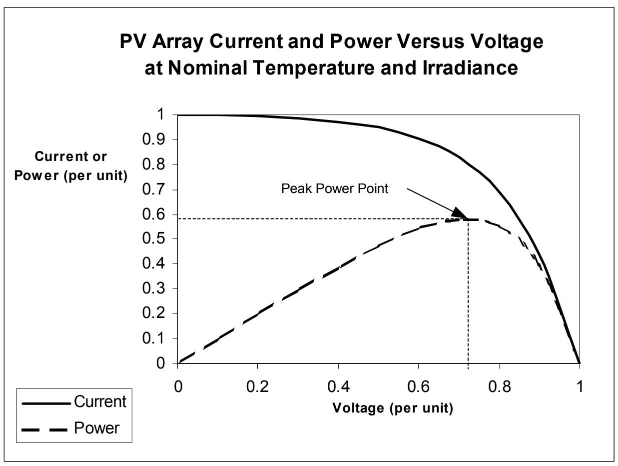

Figure 5. Normalized, Typical PV Array Current and Power as a Function of Array Voltage

Xantrex has implemented an algorithm in its three-phase inverter line that regulates the voltage on the PV array and uses the output power to the utility grid for feedback. The voltage on the array is controlled by an outer loop that adjusts the AC utility current. The voltage is then stepped up or down in discrete steps and the output power is checked to determine whether it has increased or decreased. If it has increased, then the voltage is stepped in the same direction and if it has decreased, the voltage is stepped in the opposite direction.

The MPPT controller must not only be able to precisely locate the optimum operating point on the PV array under relatively static conditions where the intensity of the sun and the temperature of the PV modules change slowly throughout the day, but must also respond quickly and track close to this power point under dynamic conditions caused by the movement and reflective enhancement of clouds. These rapid changes in irradiance result in a locus of peak power points to which the inverter voltage regulator must respond (see Figure 6). Poorly designed maximum power tracking algorithms may become "lost" or "stuck" at a undesirable operating point following these transient events. The design of a precision MPPT control algorithm that tolerates DC power transients and provides stable operation over a wide power range is a complex control problem that is difficult to simulate, and manufacturers develop their own techniques through field experience. The Xantrex power tracking algorithm has been shown to achieve a 97% to 99% utilization of the PV array by testing at DETL.

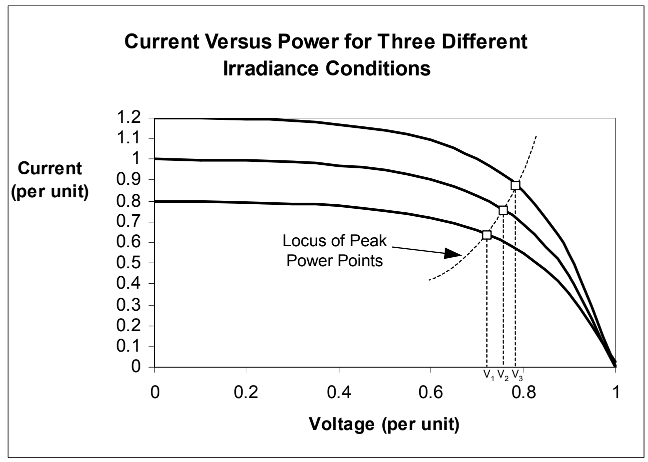

Figure 6. Normalized, Typical PV Array Current as a Function of Voltage and Irradiance

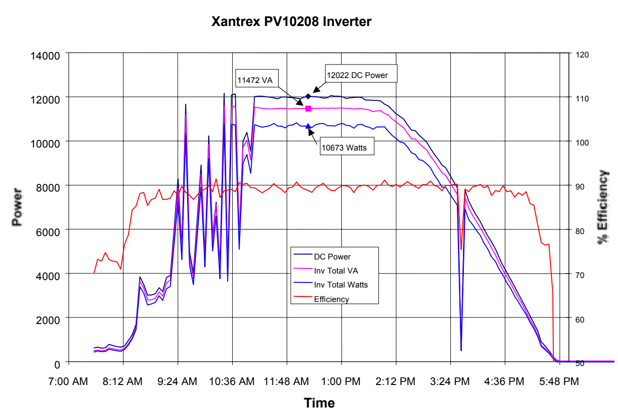

Figure 7. PV Inverter performance with total efficiency

Performance data for a system using a Xantrex PV unit is shown in Figure 7. The data is for a system operating on a day with variable irradiance.

POWER QUALITY

Another key aspect in the performance of grid-connected PV systems is that the power injected into the grid must meet utility power quality requirements. These requirements are specified in the IEEE 519 Recommended Practice [3]. The primary trade-offs that drive power quality, once a topology has been selected, are the transistor switching frequency used and the output filter components. Higher switching frequencies result in higher power quality as measured by Total Harmonic Distortion (THD), Total Demand Distortion (TDD) and the levels of individual harmonics, for a given filter configuration. This is at the expense of higher switching losses. The size of filter components is driven by the magnitude of the ripple current at the switching frequency. This ripple current decreases as the switching frequency increases.

Performance of a typical Xantrex three-phase inverter is shown in Figures 8 and 9. Figure 8 is a time domain plot of the voltage between two phases (top trace) and the current in one phase (bottom trace). Note that the 30° shift between the phase current and the phase-to-phase voltage corresponds to unity power factor operation. Figure 9 illustrates the THD of the inverter output current as a function of output power. It is important to note that the IEEE 519 requirements place limits on current TDD, rather than THD. TDD normalizes the THD and individual harmonics to the inverter's rated fundamental current.

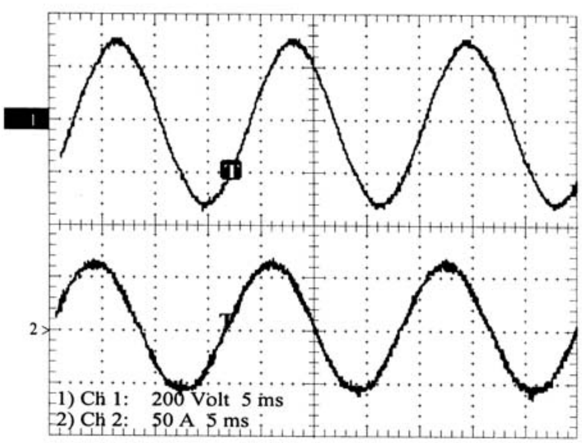

Figure 8. Time Domain Waveforms of Utility Voltage (upper) and Current (lower)

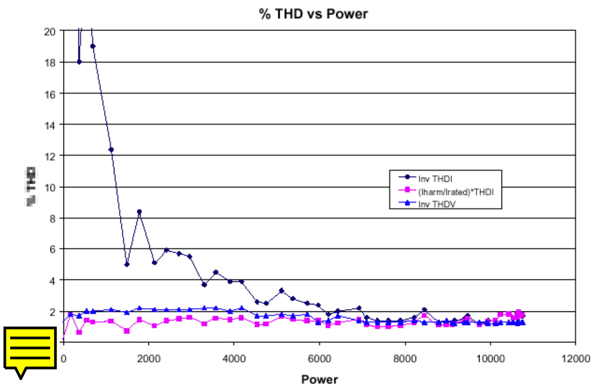

Figure 9. Current THD and TDD and Voltage THD as a Function of Inverter Power Output

ANTI-ISLANDING

Requirements given in the IEEE Std. 929-2000 [4] and UL 1741 Standards [5] define the inverter response to potential local islanding conditions when the utility is lost. To meet these interconnect standards, an active method of anti-islanding must be employed. A number of methods have been described where a perturbation of power, current, or phase angle is employed to cause unstable operation in the absence of the grid [6], [7].

The approach implemented in the Xantrex product involves a phase shifting loop as the anti-islanding perturbation. This algorithm adjusts the inverter output current phase angle at regular intervals, and the over/under voltage and over/under frequency detection is employed to bring the inverter off-line. The phase shift method is essentially a periodic attempt by the inverter to try to change the frequency at its AC output terminals. Under normal interconnection conditions, the low impedance of the grid prevents this from occurring. However, if the inverter is able to change the frequency, then the utility is no longer present and the inverter has islanded with the local load. Testing at Sandia National Laboratories has demonstrated the efficiency of this algorithm under the condition specified in IEEE 929 and UL 1741. This is shown in Figure 10, illustrating the time domain disconnection process that takes place to stop an islanding condition.

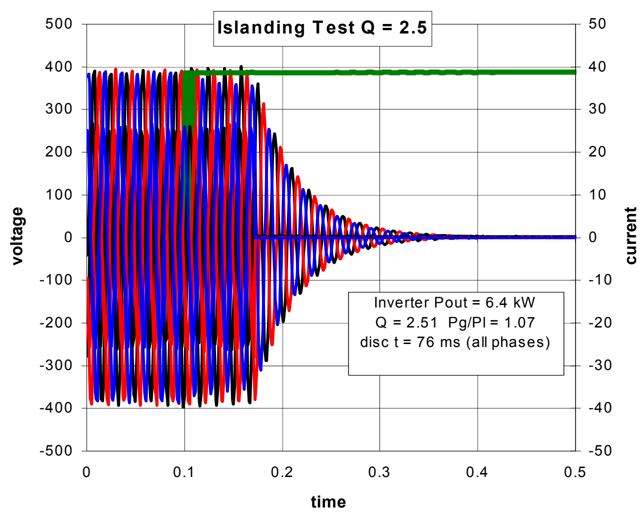

Figure 10. Xantrex PV Anti-islanding Performance

COST

All of the preceding design considerations are traded off with the cost of the equipment. In addition, ease of manufacture, production test costs and reliability considerations must be addressed.

Any inverter must be designed for ease of assembly and testing. Low component costs alone will not insure a competitively priced end product. The manufacturing and test methodology must be considered at the beginning of the design process, not as an afterthought, in order to achieve the highest overall product value. Although three-phase grid connected inverters are not yet a commodity item, there is an application by system integrators of a cost performance measure of dollars per watt.

An inverter with a better reliability rating should theoretically be able to command a higher price than one with lower reliability. Under current market conditions, it is unclear if an inverter with twice the guaranteed lifetime would be able to sell at anywhere near twice the price. As the inverter market matures and the total long-term system costs become more of a system design driver, high-reliability equipment should come of age.

CONCLUSIONS

There are a number of key design decisions for developers of three-phase grid connected systems for photovoltaic applications. These include both hardware optimization as well as in the control algorithm area. The items explored in this paper cover some of the major items: circuit topology, efficiency, maximum power point tracking, power quality, anti-islanding and cost.

It is critical to have complete and accurate data on the performance of this type of system. The Sandia National Laboratories Distributed Energy Technology Laboratory has excellent facilities for this. Test results for the Xantrex PV series of three phase systems are included showing successful operation.

REFERENCES

[1] J. Enslin, M. Wolf, D. Snyman, W. Swiegers, "Integrated Photovoltaic Maximum Power Point Tracking Converter", *IEEE Transactions on Industrial Electronics*, Vol. 44, No. 6, Dec. 1997.

[2] H. Hinz, P. Mutschler, "Voltage Source Inverters for Grid Connected Photovoltaic Systems", *Proceedings of 2nd World Conference and Exhibition on Photovoltaic Solar Energy Conversion*, Vienna, July 1998.

[3] IEEE Std 519-1992, IEEE Recommended Practice and Requirements for Harmonic Control in Electrical Power Systems, Institute of Electrical and Electronics Engineers, Inc., New York, NY.

[4] IEEE Std 929-2000, IEEE Recommended Practice for Utility Interface of Photovoltaic (PV) Systems, Institute of Electrical and Electronics Engineers, Inc., New York, NY.

[5] UL 1741, First Edition, *Standard for Safety for Inverters, Converters and Controllers for Use in Independent Power Systems*, with January 17, 2001 revisions.

[6] G. Kern, R. Bonn, J. Ginn, S. Gonzales, "Result of Sandia National Laboratories Grid Tied Inverter Testing", *Proceedings of 2nd World Conference and Exhibition on Photovoltaic Solar Energy Conversion*, Vienna, July 1998.

[7] US Patent 6219623, "Anti-islanding Method and Apparatus for Distributed Power Generation", assigned to Plug Power, Inc., Latham, NY